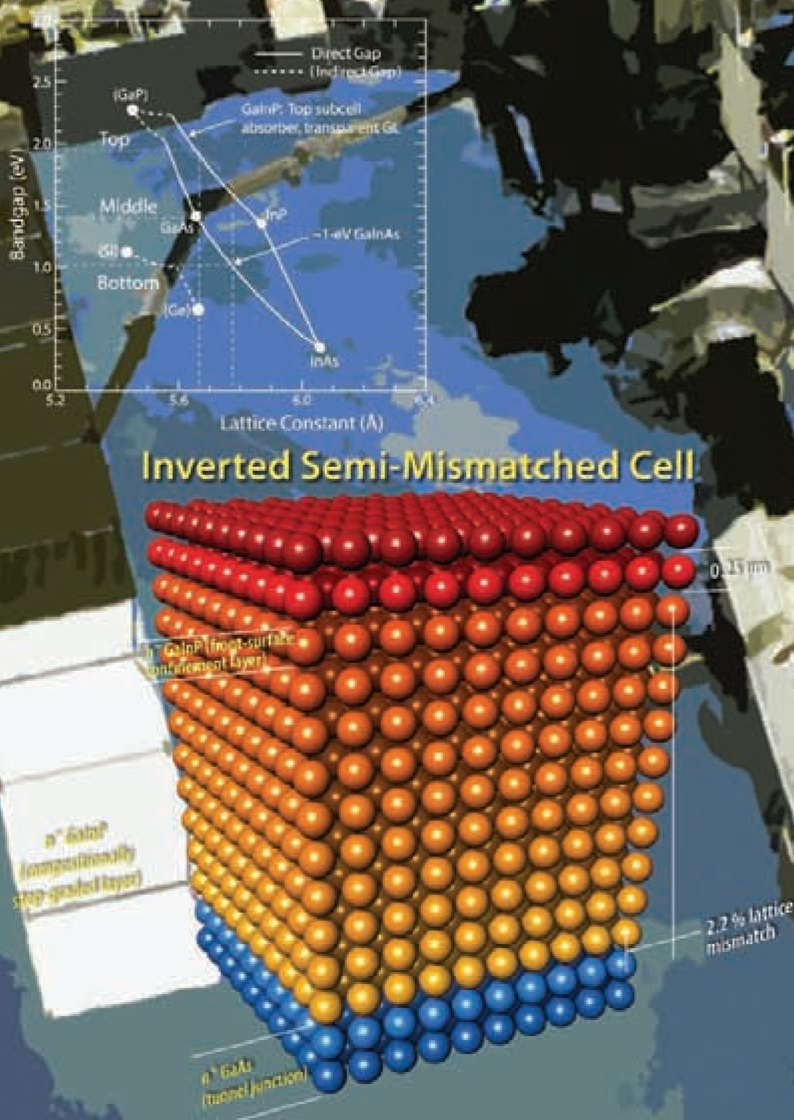
Closing the Gaps

Semi-mismatched semiconductor materials can boost solar device efficiency



In the world of solar cell design, conventional wisdom dictates that things work best when everything lines up properly—in other words, when the spacing of the atoms in one semiconductor layer of a solar device closely matches that of the adjacent layer. However, innovative research often calls for unconventional methods if we are to "build a better mousetrap"—or in this case, a more efficient solar device. The National Renewable Energy Laboratory's work on so-called "semi-mismatched" multijunction solar cells is one example of this.

A primary goal of NREL's solar energy research and development (R&D) is to create photovoltaic (PV) devices—cells and modules—that have excellent conversion efficiencies. A device's conversion efficiency is a measure of how well it uses the energy of sunlight to produce electrical energy. However, three critical "gaps" still get in the way of high efficiencies, as illustrated in Fig. 1.

Peering into the Gaps

These three gaps correlate with different aspects of solar cell R&D. The first gap is the difference between the *theoretical* efficiency of the semiconductor material used in a solar device and the efficiency of the fabricated device, as measured under the best *laboratory* conditions. For example, given certain assumptions, the theoretical best efficiency of a crystalline silicon cell is about 29%. But the top efficiency to date for a crystalline silicon cell measured in the lab is nearly 25%, which leaves us with a 4% gap.

The reasons for this gap include the efficiency losses inherent in the solar conversion process and the difficulty of fabricating a cell with the necessary properties. To overcome this gap, R&D is needed that will identify, explain, and minimize losses; enable the device to collect each photon or packet of light incident upon it; allow the photons to create the maximum number of electrical charge carriers; and make sure the charge

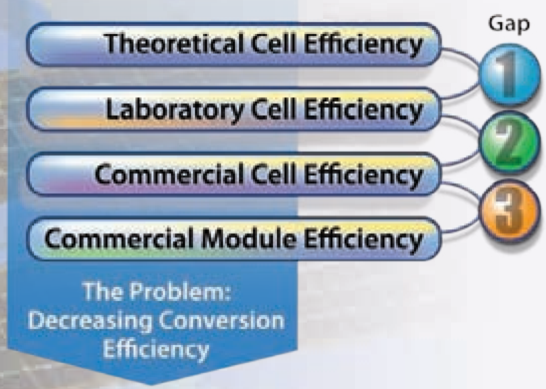


Figure 1. The three efficiency gaps for solar cells and modules

carriers last long enough to contribute to generating a current.

The second gap is the difference between the efficiencies of *laboratory* cells and the efficiencies of those produced in *commercial* production lines. This gap may be a result of scaling up the fabrication process to produce larger devices. Also, in the manufacturing environment, higher throughput is required and fabrication conditions are often less controlled.

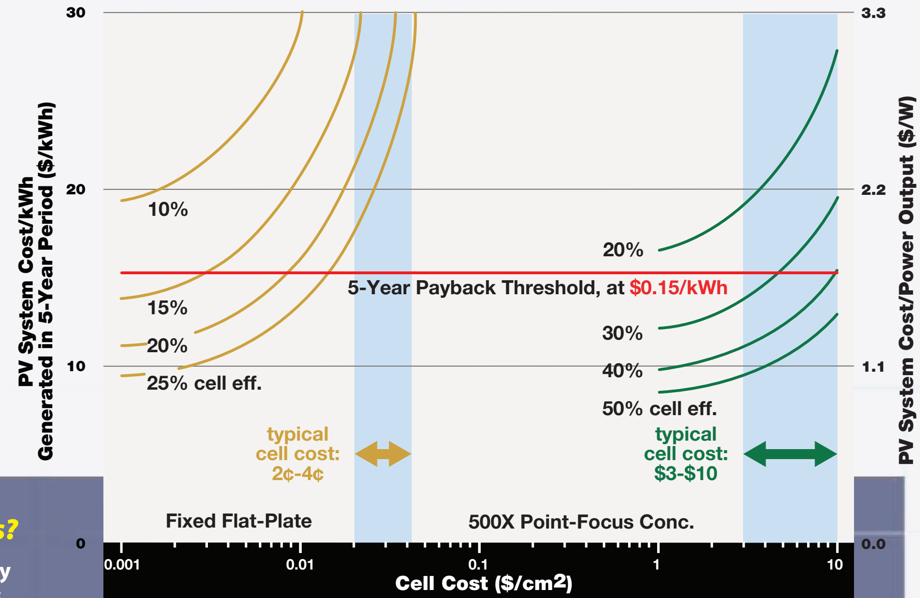
The third gap is the difference between *cell* efficiencies and *module* efficiencies. This gap will narrow when we can do at least three things: minimize the electrical losses that occur when cells are wired into circuits, bring the active area of the module closer to the cell area, and maximize the optical transmission of the protective encapsulant material.

Working in Tandem

Here we address several issues surrounding the first two gaps, focusing on an inverted semi-mismatched solar cell being developed at NREL. NREL's research is being carried out to develop laboratory cells with measured efficiencies closer to theoretical efficiencies, and to address design factors that will lead to more efficient manufactured cells and modules.

NREL's innovations could result in increasingly higher efficiencies as new devices are optimized. In turn, these devices will play an important role in the need for high-efficiency PV devices in space applications, as well as on land, for large-scale power production.

The multijunction or tandem cell has been the focus of R&D at NREL and other laboratories for a few decades. In single-junction cells, the energy of the illuminating light that is below the bandgap of the cell material is lost; thus, it cannot be used to generate electricity. (The bandgap—not



Why Worry About High Efficiencies?

High efficiencies are important because they are indicators of cost-effective solar devices. The cost-effectiveness of a PV system depends on the cell's cost per unit area. To determine a suitable cost range for a cell, researchers from Spectrolab, Inc., and NREL adapted[1] an analytical methodology by Swanson[2]. The PV system's cost per kilowatt-hour over a 5-year payback period was calculated as a function of the cell's cost per unit area, taking into account various assumptions relating to efficiencies, costs, packaging, and solar resources.

As shown, electricity costs for both flat-plate and concentrator systems can fall below 15 cents per kilowatt-hour (a near-term R&D target value) when high efficiencies are combined with low cell costs. Note two families of curves: those for flat-plate systems, requiring very low cell costs, and those for concentrator systems, which can tolerate relatively high cell costs.

The cell costs of flat-plate systems need to range from 0.1 to 1 *cent* per square centimeter, for cost-effective, 20%-efficient cells. In contrast, for concentrator systems with 30%-efficient cells, a cell cost of 1 to 5 *dollars* per square centimeter—which is 500 to 1000 times greater—is cost-effective. The challenge for flat-plate technologies is to reduce today's typical cell costs of 2 to 4 cents per square centimeter by an order of magnitude, while maintaining cell efficiencies of 20%. For concentrator systems, 30%-efficient cells are cost-effective now; the challenge is to reach efficiencies in the 40% to 50% range for even greater cost-effectiveness.

Sunlight is a "dilute" resource, and low-efficiency systems require very large areas of active PV material and all packaging and structural materials, such as metal, glass, and plastic. However, high-efficiency solar cells have at least two benefits: the module area needed for a given electricity output is greatly reduced, and module and balance-of-system costs are highly leveraged. At 500x concentration, relatively high cell costs per area are acceptable. Therefore, taking cell efficiencies into the 40% to 50% range may well be the best path to cost-effectiveness.

1. R.R. King and others, *Intl. Conf. on Solar Concentrators for the Generation of Electricity or Hydrogen*, 1–5 May 2005, Scottsdale, AZ. NREL/CD-520-38172 (2005).
2. R. Swanson, *Prog. Photovolt. Res. Appl.* 8, 93–111 (2000).

one of the "gaps" discussed here—is the energy needed to dislodge an outer electron from its bond.) The multijunction concept allows a PV device to capture and use this lost energy, resulting in a higher conversion efficiency and thus greater electrical output.

During the early to mid-1990s, NREL researchers developed and patented a two-junction device with high efficiency. The top cell was made of gallium indium phosphide (GaInP), which has a bandgap of ~1.9 electron-volts (eV). The bottom cell was made of gallium arsenide (GaAs), with a bandgap of ~1.4 eV. Earlier GaAs cells had efficiencies exceeding 25% under concentrated sunlight. Adding the GaInP layer to the GaAs layer further boosted the overall cell efficiency by capturing more of the energy in the spectrum.

This concept later evolved into three-junction devices, again with the goal of capturing more useful energy otherwise lost to the cell. One prominent system is made of GaInP / GaAs / germanium (Ge). The third or lowest layer, with a bandgap of ~0.7 eV, captures the long-wavelength, low-energy "red" light that passes unused through the two upper layers. This device is lattice matched, which means that the spacing of atoms in the Ge layer very closely mimics the spacing of the atoms in the GaAs layer above it.

When a crystal is grown through an epitaxial process—in which the overlying crystal has the same orientation as the underlying one—matching keeps the crystal lattice from being deformed at the transition point from one layer to another. Deformed layers—structural defects in the regularity of the crystal lattice, such as threading dislocations and stacking faults—negatively affect the movement of charge carriers through the material and thus reduce the performance of the device.

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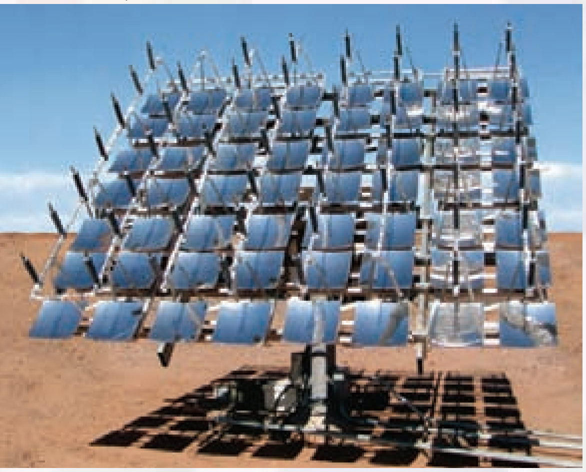

Concentrating Technologies Microdish configured for Spectrolab multijunction cell

Researchers at NREL and elsewhere decided to develop a third layer having a more optimal bandgap; analyses indicated that material with a 1-eV bandgap could improve overall device efficiency as much as 10%–12%. The dilute nitride of a GaInAsN layer has such a favorable bandgap and is lattice matched to GaAs. However, efficiency measurements of GaInP / GaAs / GaInAsN devices have not been promising.

A logical next step was to investigate a four-junction device consisting of GaInP / GaAs / GaInAsN / Ge, which has a bandgap sequence of 1.9 / 1.4 / 1.0 / 0.7 eV. The efficiency of this device is about 31% at 500 suns; further optimization may boost that number.

Inverting and Mismatching to Increase Efficiency

Design options for some PV device structures based on lattice-matched epitaxy are constrained by the limited number of commercially available crystalline substrate materials (Ge and GaAs, for example). However, the "design space" increases substantially when we consider designs involving lattice-mismatched layers.

Traditionally, lattice-mismatched approaches have been dismissed because of problems such as high defect density, rough surfaces, and cracking or bowing of layers. At NREL, the goal is to produce semi-mismatched lattice heterostructures that look and perform like lattice-matched ones. In the process, we want to attain the highest charge-carrier lifetimes, the thinnest structures, and the flattest wafers possible.

Mark Wanlass and his colleagues in NREL's High-Efficiency Solar Cell team are pursuing a novel tandem cell approach. One key innovation involves growing the cell layers in inverted order; this approach could have several cost and manufacturing benefits and boost efficiency, as well. Another innovation is to incorporate a transparent, compositionally step-graded layer to accommodate lattice mismatching without penalizing cell efficiency.

Figure 2 illustrates the basic layer-cake structure of the inverted GaInP / GaAs / gallium indium arsenide (GaInAs) cell. The structure is considered to be inverted because it is grown upside down—that is, the top layer is grown on a substrate, then the next two main "active" subcell layers are deposited. In actual operation, the stack is flipped so that sunlight strikes the top subcell first.

The top two active subcell layers are lattice matched. A 1.9-eV top active layer of GaInP is deposited on a GaAs substrate before a 1.4-eV middle active layer is added. Each active subcell layer actually has a double-heterostructure configuration; this means the active material is sandwiched between thin layers of material with a somewhat higher bandgap. This configuration confines the charge carriers to the active subcell layer. Each active subcell layer also contains an n/p junction. The GaInP active subcell layer is sandwiched between negatively (n) and positively (p) doped aluminum indium phosphide (AlInP) to form the top subcell. Similarly, the GaAs active subcell layer is sandwiched between n- and p-doped GaInP to form the middle subcell.

The lowest (third) active subcell layer is made of GaInAs, with a bandgap of ~1.0 eV, and is sandwiched between GaInP layers to form a double-heterostructure bottom subcell. The GaInAs lattice is mismatched 2.2% in comparison to the lattices of GaInP and GaAs. To accommodate this mismatch, a compositionally step-graded

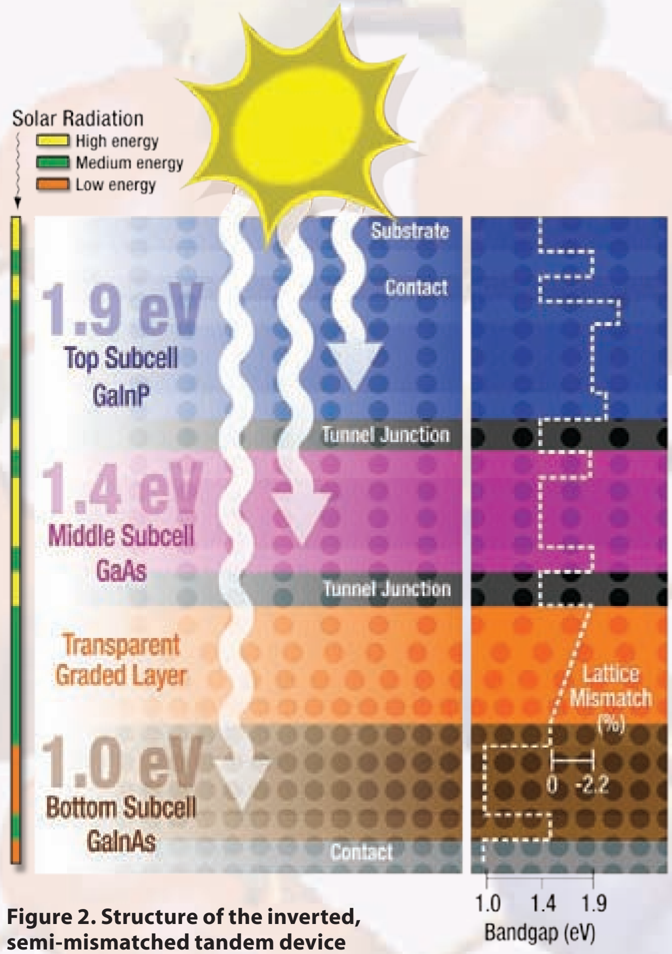

Figure 2. Structure of the inverted, semi-mismatched tandem device

layer of GaInP is included between the middle and bottom subcells. In detail, the transparent graded layer consists of nine 0.25-micrometer-thick steps that differ in composition from one another by 0.03 fractional percent Ga. Significantly, although cross-sectional transmission electron microscopy shows substantial defects in this graded layer, it identifies only a modest dislocation density in the active subcell layer.

The overall tandem cell is a two-terminal, monolithic device. In other words, individual subcells are not grown separately and then stacked mechanically. Rather, all subcells are grown in one continuous depositional process—in this case, by atmospheric-pressure metal-organic vapor-phase epitaxy in a system built by NREL. Layers of heavily p- and n-doped GaAs form "tunnel junctions" between the subcells, thus allowing charge carriers to move through the entire device, and front and back electrical contacts gather the cell's current.

The device's monolithic structure makes it relatively easy to manufacture in comparison to mechanically stacked devices. But to optimize the device, we must adjust the thicknesses of each subcell so that the photocurrents of each are the same. Otherwise, in a series-connected device, the subcell with the lowest photocurrent will be the limiting factor in regard to the current of the overall cell.

Seeing the Benefits

As PV researchers work diligently to overcome such performance gaps as the discrepancies in conversion efficiencies found in solar cells, this inverted GaInP / GaAs / GaInAs cell is a significant step forward. NREL has confirmed an efficiency of 37.9% at 10.1 suns (and a temperature of 25°C, a low aerosol optical depth air mass of 1.5 direct, and an area of 0.2428 cm^2); this is a very encouraging number for a device that has yet to be optimized.

The peak efficiency at such a low concentration ratio indicates that efficiencies exceeding 40%—perhaps as high as 45%—at several hundred suns should be achievable in the near future, once a true concentrator version is fabricated. Such high efficiencies should enhance the viability of terrestrial concentrator systems for cost-effective power generation.

Some key benefits of this design are that the device can be mounted on a surrogate substrate—or "handle"—of choice, and contact with a heat sink can also be achieved, which helps to manage the thermal issues of the concentrator cell. If it is composed of some strong, flexible material such as metal foil or kapton polymer, the handle can provide a robust device in comparison to one processed on relatively fragile Ge or GaAs substrates.

Handle-mounted, ultra-thin device fabrication is a natural consequence of the inverted-structure approach, which also has a number of advantages. These include potentially low cost, the ability to make use of back-surface reflectors, and possible reclamation or reuse of the parent crystalline substrate (e.g., to reclaim the relatively scarce, expensive Ga in a GaAs substrate).

Looking Ahead

Optimizing the inverted cell will shrink its performance gaps further. And other materials, designs, and methods will undoubtedly be explored in the pursuit of higher efficiencies. So, whether NREL's researchers are developing silicon-based, thin-film, or so-called "third-generation" PV technologies, one key objective prevails: to close the gaps and thus create even more efficient cells—cells that can be produced at lower cost while exhibiting greater reliability and stellar performance.

For more information

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